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Magnesium diboride superconducting RF resonant cavities for high energy particle acceleration

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Abstract
Arguments in support of any particular superconducting coating must be framed in terms of its fundamental thermodynamic properties. The superconducting transition temperature, T_c, determines the surface resistance, and thus the Q of the cavity. This must remain sufficiently high that the system can be driven at the required field gradients and frequencies without leading to excessive power loss. In this regard the 39 K T_c of MgB_2 is advantageous. With an anticipated maximum accelerating field, E_{acc}^{MAX}, of 77 MV m^{-1} and a BCS surface resistance, R_s^{BCS} (4 K, 500 MHz), of 2.5 nΩ as discussed later, MgB_2 represents an interesting possibility as a coating for SRF cavities. In addition, the higher H_{c2} of MgB_2 than Nb results in a slightly lower estimated trapped flux sensitivity. Recent measurements of an MgB_2 film at the Los Alamos National Laboratory (LANL) have shown an RF surface resistance lower than that of Nb at 4 K, which is proof-of-principle evidence of the attractiveness of MgB_2. Our calculations are based conservatively on 4 K operation at 500 MHz. However, with a T_c of 39 K, MgB_2-coated cavities should be less susceptible to thermal breakdown than low-T_c ones. Superconducting materials for use at GHz frequencies at voltage gradients >40 MV m^{-1}, a recently cited target, will require both low R_s (high T_c) and high H_{sh} values. With a T_c of 39 K, MgB_2 clearly has the potential to reduce R_s^{BCS} if the films are well prepared and free from defects and particles. Additionally, while the H_{c1} for MgB_2 is relatively low, the superheating critical field, H_{sh}, is higher than that of Nb. Currently, there is some debate about the exact roles of H_{c1} and H_{sh} in the determination of E_{acc} limits. However, the higher values of H_{sh} for MgB_2 do suggest the possibility of enhanced E_{acc} values. The exact roles of H_{c1} and H_{sh} should be further investigated. Techniques exist that may enable cavity-like structures to be internally coated with a MgB_2 film.

1. Introduction

Superconducting RF (SRF) cavities for electron accelerators represent a well established technology benefiting from some 30 years of research and development. Since the late 1970s SRF cavities have accelerated beams in many of the world's large lepton and hadron machines [1–3].

1.1. Lepton accelerators/colliders

The first machine to use SRF cavities on a large scale was the 32 GeV electron/positron collider [$e^-(32)/e^+(32)$] TRISTAN at KEK with 32 cavities (5 cells, 508 MHz). Other important machines are/were (i) HERA at DESY, Hamburg, with 16 cavities (4 cells 500 MHz), (ii) LEP-II at CERN with 272 cavities (4 cells, 352 MHz), (iii) CEBAF at Jefferson Lab with 338 cavities (5 cells, 1.5 GHz), (iv) the TESLA test facility (TTF) linac at DESY, with two superconducting accelerator modules each with 8 cavities (9 cells, 1.3 GHz)—TESLA itself is expected to consist of a pair of e^-/e^+ linacs (collision energy 500 or 800 GeV), energized by 19 712 such 9-cell Nb cavities [4, 5].

1.2. Hadron colliders

In comparison to its activity with regard to lepton accelerators, high energy physics has produced relatively few pure hadron colliders. Notable machines are: Tevatron (p–p^-, Fermilab), RHIC (ion–ion, BNL), SPS-collider (p–p^-, CERN), and UNK (p–p^-, IHEP, Serpukhov). The first *hadron* colliders to use elliptical-type superconducting cavities will be the LHC with two groups of 8 single cells operating at 400 MHz [6], and the spallation neutron source (SNS) at Oak Ridge National Lab (ORNL) that includes a superconducting proton linac section with 11 low β (0.61) and 12 high β (0.81) cryomolecules containing 33 and 48 cavities (6 cells, 805 MHz), respectively [7, 8].

1.3. SRF cavity materials and fabrication

The superconducting cavities of all the machines mentioned above (past, present and in the planning stages) are fabricated from either monolithic ('bulk') Nb or bimetallic Nb/Cu the relative advantages of which are discussed in [9, 10].

Following the KEK (TRISTAN) experience most groups evidently favour the bulk-Nb approach to cavity fabrication—Cornell University, DESY (HERA and TESLA), Jefferson Lab/ORNL (CBAF and SNS) [11]. The fabrication of a bulk-Nb cavity generally begins with the deep-drawing of a plate of pure Nb (RRR 200–300) to form 'half-cells' which are then machined (trimmed), assembled into multicell cavities by EB welding, and carefully surface treated, e.g. [4, 12], see also section 4.2. To avoid the EB welding step DESY has investigated the fabrication of seamless bulk Nb cavities by the hydroforming of seamless spun- and deep-drawn Nb tubes [13].

On the other hand for LEP-II a decision was made to fabricate 'composite' cavities, made by sputter-coating a Nb film onto the polished interior surface of a pre-formed Cu shape. In addition to the significant cost reduction stemming from the smaller amount of Nb required to fabricate a cavity, two other advantages claimed for this approach are the higher thermal stability contributed by the cooled high purity Cu substrate, and a lower sensitivity to the ambient magnetic field as compared to bulk Nb cavities. This successful demonstration of Nb/Cu technology has led to its being selected for the LHC accelerating system presently under way [6]. For high gradient applications such as TESLA, however, Nb-film/Cu has been shown to be inadequate due to the steep Q slope that accompanies the higher gradients. To overcome this, while still taking advantage of the stability offered by the Cu substrate and at the same time to avoid problems caused by welded seams, other groups have investigated the use of bulk bimetallic Nb/Cu tubes made by hot isostatic pressing [9] or explosion bonding [13, 14] and gone on to shape cavities, again by hydroforming.

As for new materials, the search for improved superconductive coatings (with higher T_c and H_{c2}) continues. Superconductors considered have been the A15 compounds Nb_3Sn [15] and V_3Si, the B1 compounds NbN, NbC, and NbTiN [16] and the high-T_c material YBCO [17, 18]. But with the recent discovery of superconductivity at 39 K in MgB_2 several groups have begun to consider it as an SRF cavity coating material [19, 20]. MgB_2, has a higher T_c (39 K) than the 'low-T_c' compounds and a longer coherence length than YBCO. Compared to YBCO, MgB_2 is less reliant on special substrates. As a line compound it is rather insensitive to impurity content, and has strongly linked grain boundaries. As an SRF cavity coating it has the potential (compared to Nb but still to be achieved) for lower BCS surface resistance, lower trapped flux sensitivity, and depending on how the estimate is made, a higher maximum accelerating field.

2. Normal-metal cavities [1, 21]

2.1. The shunt resistance R_{sh}

The Q (quality factor) of a cavity is defined in terms of the ratio of mean stored energy to energy dissipated per cycle, hence $Q = \omega U/P_c$. Next, representing the cavity in terms of an inductance L and capacitance C such that $U = (1/2)CV^2$ we find at resonance ($\omega_0^2 = 1/LC$) that $Q = \sqrt{\{(C/L)\}}R_{sh}$. Thus Q is determined by the shape of the resonator (hence C/L) and R_{sh}. The latter should be as large as possible. We show below that R_{sh} is inversely related to the cavity's surface resistance, R_s.

2.2. The surface resistance, R_s

The factor Q which we have defined above as $\omega U/P_c$ has also been defined as G/R_s where G is a 'geometry factor' (with the units of resistance). The cavity-shape dependence of Q is embodied in G which for SRF accelerator cavities generally lies between 200 and 300 Ω [1, 22] (see [23]). This seems to define R_s as the reciprocal of R_{sh} leading to the obvious conclusion that high Q and power conversion efficiencies requires large R_{sh} and small R_s. These goals are simultaneously achieved with the use of superconducting cavities.

2.3. Limitations of normal-metal cavities— R_s and the anomalous skin effect

If an electromagnetic (EM) field is supported by a conducting medium the induced currents are confined (exponentially) to a surface layer of thickness δ, the skin depth. When the skin depth is much greater that the electron mean free path (mfp, l) the conduction electrons experience the normal resistance, ρ, of the medium—the 'normal skin effect'. But, if somehow l starts to exceed δ a kind of electromagnetic size effect, the 'anomalous skin effect', sets in and, in this limit, enhances the resistivity according to $\rho_{eff} = (l/\delta_{eff})\rho$, where δ_{eff} is a new 'anomalous skin depth'. In a cavity being cooled to cryogenic temperatures the anomalous skin effect has a strong influence on the surface resistance, now $R_{s,anom}$. The following analysis, which takes into account the fact that both $l(\rho) = (6.56 \times 10^{-16})/\rho_{\Omega m}$ and $\delta(\rho) = (2\rho/\mu_0\omega)^{1/2}$ are temperature

dependent, finds a way of comparing the temperature responses of $R_s = (\mu_0\omega\rho/2)^{1/2}$ and $R_{s,anom}$. By manipulating δ, the surface resistance $R_s(T)$ is then compared in the normal and anomalous skin effect regimes:
Normal ($l \ll \delta$)

$$\delta = \left(\frac{2\rho}{\mu_0\omega}\right)^{1/2}$$

$$\text{which returns} \quad R_s = \left(\frac{\mu_0\omega}{2}\right)^{1/2}\rho^{1/2} \tag{1}$$

$$\text{i.e.,} \quad R_s \text{ is proportional to } \rho^{1/2} \tag{1A}$$

Anomalous ($l \gg \delta$)

$$\delta_{\text{eff}} = \left(\frac{2\rho_{\text{eff}}}{\mu_0\omega}\right)^{1/2}$$

leading via $\quad \rho_{\text{eff}} = (l/\delta_{\text{eff}})\rho$ to

$$R_{s,\text{anom.}} = \left(\frac{\mu_0\omega}{2}\right)^{2/3}k^{1/3}$$

$$\text{in whick } k = l\rho = 6.56 \times 10^{-16}\ \Omega\ \text{m}^2 = \text{const.} \tag{2}$$

$$\text{hence} \quad R_{s,\text{anom.}} = \text{constant.} \tag{2A}$$

In the normal skin effect regime $R_s(T)$ decreases with temperature, as expected, and does so according to $\rho^{1/2}(T)$. But upon entering the anomalous region $R_{s,anom}$ becomes independent of ρ and hence T. Below this transition region no advantage is gained by further lowering the temperature of the Cu cavity (assuming $f = 500$ MHz, $\rho_{\text{Cu,300 K}} = 1.5 \times 10^{-8}\ \Omega$ m) whose $\text{RRR}_{\text{eff}} = R_{s,300\text{ K}}/R_{s,anom} = 5.44/1.39 = 4$. If the frequency is increased to 1.5 GHz (e.g. CEBAF) both R_s and $R_{s,anom}$ increase and RRR decreases to 3, both very low for high purity Cu—hence the need for superconducting cavities.

3. Superconducting cavities

3.1. BCS surface resistance

Although possessing zero DC resistivity superconductors possess a non-zero RF resistivity that decreases with temperature. The BCS surface resistivity is given by

$$R_s^{\text{BCS}} = \frac{A}{T}\omega^2 \exp\left(-\frac{\Delta_0}{k_B T}\right) \tag{3}$$

where the prefactor A depends on materials parameters such as penetration depth, λ, coherence length, ξ, and l. In BCS theory the depairing (gap) energy 2Δ at 0 K ($2\Delta_0$) is equal to $3.52\,k_B T_c$. For the Nb surfaces in current use $T_c = 9.25$ K and $2\Delta_0/k_B T_c = 3.9$. Then substituting 10^5 for $4\pi^2 A$ (as in [21]) the surface resistance is:

$$R_s^{\text{BCS}}\ (\text{n}\Omega) = \left(\frac{1}{T}\right)10^5 f_{\text{GHZ}}^2 \exp\left(-\frac{18}{T}\right) \tag{4}$$

which at 4 K, 1.5 GHz is equal to 620 nΩ in reasonable accord with experiment [22, 24]. At 4 K, 500 MHz (our selected 'reference condition') R_s^{BCS} is 69 nΩ. This is a factor of about 10^5 less than the room-temperature R_s of Cu which according to equation (1) is 5.4 mΩ.

Further improvements in cavity properties have been sought by replacing Nb (experimentally) with superconductors having higher T_cs and upper critical fields, H_{c2}.

3.2. Benefit from increasing T_c

For superconductors with higher T_cs than Nb the BCS surface resistance becomes correspondingly smaller. For example Nb_3Sn, with $T_c = 18.3$ K and $2\Delta_0/k_B T_c = 4.5$, R_s^{BCS} (assuming no change in the prefactor A) becomes:

$$R_s^{\text{BCS}} = \left(\frac{1}{T}\right)10^5 f_{\text{GHZ}}^2 \exp\left(-\frac{41}{T}\right) \tag{5}$$

which at 4 K, 500 MHz is equal to 0.22 nΩ, illustrating how an increase in T_c can lead to a significant reduction in surface resistance. As mentioned above, the benefits of higher T_c have led to the consideration of Nb_3Sn, V_3Si, NbN, NbC, NbTiN, and YBCO. But, as recognized by the several groups that have also considered it [19, 20], MgB_2 has a higher T_c (39 K) than the low-T_c compounds and a longer coherence length (plus other advantages) over high-T_c YBCO.

3.3. Benefit from increasing H_{c2}—as it relates to residual surface resistance and trapped flux

The total superconductor surface resistance, R_s^{SC} is the sum of R_s^{BCS} and a 'residual resistance', R_{res}, that takes into account the effect of surface imperfections in general (R_{imp}) and trapped magnetic flux (R_{fl}) [22, 24]. In the presence of the RF field, the trapped flux contributes a kind of dynamic resistance originating in the normal cores of the fluxoids (each of area $\pi\xi^2$) which cover a fraction, H/H_{c2} of the surface of normal-state surface resistance, R_s^{NORM}. An expression for R_{fl} can be deduced by: (i) expressing the field H of N fluxoids per unit area in the form $H = N\phi$ and (ii) invoking the 'area-consumed' model for H_{c2}, namely $H_{c2} = \phi/\pi\xi^2$. The magnetically induced residual resistance then becomes:

$$R_{\text{fl}} = (N\pi\xi^2)R_s^{\text{NORM}} = N\phi\left(\frac{\pi\xi^2}{\phi}\right)R_s^{\text{NORM}} = \left(\frac{H}{H_{c2}}\right)R_s^{\text{NORM}}. \tag{6}$$

To retain the advantage of superconductivity we would expect R_{fl} to be certainly no more than R_s^{BCS}, thereby defining an upper limit to H and hence the extent to which the cavity should be shielded. In the case of Nb, with a residual R_s^{NORM} of 3.4 mΩ and an H_{c2} of 0.24 T the equality is achieved with a stray field of 5 μT. This deduced value of R_{fl}, namely 14 nΩ μT^{-1}, comparable to the 3.5 nΩ μT^{-1} reported by Vallet *et al* [25], emphasizes the need for effective magnetic shielding, e.g. [11].

In equation (6) H_{c2} is needed as a calibration factor for quantifying the relative area occupied by the trapped fluxoids. Consequently it has the form of the Bardeen–Stephen relationship for flux-flow resistivity. But the parallelism is strictly formal. The cavity, being in the Meissner state, does not support a flux lattice. Trapped fluxoids, which can give rise to R_{fl} values as high as 100 nΩ [26], are localized at surface defects of various kinds, e.g. 'field-emission' sites or other such resistive patches that can lead to 'thermal breakdown' [26], see below.

4. Present generation superconducting cavities—properties and degradation mechanisms

4.1. Peak surface fields

The accelerating field, E_{acc}, is defined as the accelerating voltage divided by effective cavity length, d. With a typical cavity shape for electron machines, e.g. TESLA cavities, a peak surface magnetic field, H_{pk} (Oe) is related to E_{acc} (MV m^{-1}) according to:

$$H_{pk} = 42E_{acc}. \quad (7)$$

The maximum allowable value of E_{acc} thus corresponds to some $H_{pk,max}$, the RF surface critical magnetic field or 'superheating critical field', H_{sh}. At microwave frequencies each cycle of the applied field exceeds some critical field (the thermodynamic H_c or the lower critical H_{c1}) in less time than it takes to nucleate a normal region (or fluxoid), typically 10^{-6} s [27]. Accordingly, in type-I superconductors (e.g. Pb) $H_{sh} > H_c$ and in type-II superconductors $H_{sh} > H_{c1}$. According to GL theory [28, 29], see also [30]:

$$H_{sh} \approx \frac{0.89}{\sqrt{\kappa}} H_c, \qquad \kappa \ll 1 \quad (8a)$$

$$H_{sh} \approx 1.2 H_c, \qquad \kappa \approx 1 \quad (8b)$$

$$H_{sh} \approx 0.75 H_c, \qquad \kappa \gg 1. \quad (8c)$$

For the low-κ superconductor Nb ($H_c = 2000$ Oe) $H_{sh} = 2400$ Oe hence, based on equation (7), $E_{acc}^{MAX} = 57$ MV m^{-1}. The highest E_{acc} ever reached is $\sim$45 MV m^{-1} with a TESLA-shape single cell cavity. Some authors claim that the 'reference field' for type-II superconductors should be H_{c1}, not H_c [27, 31]. But the H_{sh} matter, particularly with regard to high κ/high-T_c superconductors, is still under investigation.

4.2. Field emission

Field emission (FE) [19, 32] from asperities and/or particles on the cavity surface is a heat generating mechanism. Caused by field-emitted electrons impinging on the cavity surface, it brings about an exponential decrease in Q_0. Field emission as well as thermal breakdown (see below) are suppressed or eliminated by introducing elaborate quality control measures into each step of the cavity fabrication sequence, as explained in [4] with particular reference to TTF cavities. Quality control begins with detailed microscopic examination of the starting Nb sheet, after which cleaning operations are introduced at each step of the fabrication process (half-shell, dumbbell, completed cavity). For example the cavity-cleaning steps taken at DESY begin with (i) buffered chemical polishing (BCP), (ii) high pressure rinsing (HPR) with ultraclean water and drying in a class-100 clean room, (iii) annealing for 2 h/800 °C, (iv) rinsing and drying, (v) UHV outgassing at 1350–1400 °C during which the RRR doubles to about 500, then continue with further 'post-purification' and BCP operations, and conclude with clean-room drying. Any remaining surface defects may be removed by high-power pulse processing or helium ion bombardment (helium processing). Many TESLA cavities have shown no FE.

4.3. Thermal breakdown

Thermal breakdown [26, 32] is a cavity quench resulting from heat generation in submillimetre size resistive surface defects—particles or pits. As for FE the effect can be reduced by suitably addressing the processing techniques—contamination/defect control of initial Nb material coupled with an elaborate cleaning regime. Attention should also be paid to the cryostability of the cavity by increasing RRR (see above) and improving thermal conduction between the RF surface and the liquid helium.

4.4. Q_0 degradation

The unloaded quality factor, Q_0, or the cavity RF surface resistance ($=G/Q_0$) gets degraded due to heating of the RF surface as a result of: the formation of niobium hydride during slow cool-down, so-called 'Q disease', insufficient cooling through the Nb wall, impingement of field-emitted electrons, enhanced magnetic field at grain boundaries. Regarding Q disease, it has been known that baking the cavity at >600 °C can degas the hydrogen and eliminate this problem. A recent hot topic of research is the Q drop at high fields, $E_{acc} > 25$ MV m^{-1}. Some have shown that this can be solved by *in situ* baking at $\sim$100 °C for longer than 1 day, but no one theory can explain all the observations [33].

5. MgB_2 as an SRF cavity coating material

The suitability of MgB_2 for RF cavity use is discussed in terms of the important performance parameters and characteristics introduced above, namely: surface resistance (R_s) and its susceptibility to trapped flux (R_{fl}), superheating critical field (H_{sh}) and its associated maximum accelerating field (E_{acc}^{MAX})—see [19].

5.1. Surface resistance

The surface resistance, R_s, is regarded as the sum of a BCS surface resistance and a residual component, R_{res}. The BCS surface resistance given by equation (3) is often written in some condensed form such as:

$$R_s^{BCS}\ (\mathrm{n\Omega}) = (1/T)10^5 f_{GHz}^2 \exp(-\Delta_0/kT). \quad (9)$$

For Nb ($T_c = 9.25$ K, $2\Delta_0/k_B T_c = 3.9$) at 500 MHz we have shown that $R_{s,4\ K}^{BCS} = 69$ nΩ. In the case of MgB_2 we do not know how R_s responds to the existence of two energy gaps [34]: about 2.7 and 6.7 meV corresponding to $2\Delta_0/k_B T_c$ values of 1.6 and 4, respectively. Considering both gaps the corresponding R_s^{BCS} (500 MHz, 4 K) would be 2.5 nΩ and 2.3×10^{-5} nΩ. We cannot be sure which of these gaps would be operative or whether we should consider a single anisotropic gap (see [35, 36]). But taking the more conservative approach, even the smaller gap provides MgB_2 at 4 K with an R_s^{BCS} less than that of Nb by a factor of 28.

5.2. Residual surface resistance

The residual surface resistance, R_{res}, has essentially two components: one of them, R_{imp}, has to do with the metallurgical condition of the surface (grain boundaries, impurities, etc [22]) and the other, a more well defined magnetic contribution, R_{fl}, due to the presence of trapped flux corresponding to some stray magnetic field, H. Interacting with RF surface currents, the resulting trapped fluxoids contribute a kind of dynamic resistance originating in their normal cores (each of area $\pi\xi^2$) which cover a fraction, H/H_{c2}, of the cavity surface (normal-state surface resistance,

R_s^{NORM}). It follows (in parallel with the usual analysis of Bardeen–Stephen flux-flow resistivity—but see above) that $R_{fl} = H/H_{c2}R_s^{NORM}$. Ideally we would like R_{res} (and certainly its component R_{fl}) to be negligible compared with R_s^{BCS}, but in practice this is not always the case. Thermal breakdown has in fact led to R_{fl} contributions as high as 100 nΩ [14].

With regard to MgB_2, measurements at LANL have yielded 500 MHz-estimated 4 K R_s values as low as ~35 nΩ [37, 38]. As for possible R_{fl} contributions to R_{res}, the effect of the high resistivity of films now being produced—about $\rho_n = 50\,\mu\Omega$ cm [34, 39] leading to R_s^{NORM} (500 MHz) = 31 mΩ—is somewhat moderated by the higher H_{c2} (say 10 T) of MgB_2 such that $R_{fl}/H = 3$ nΩ μT^{-1}. Although R_{fl} is less sensitive to trapped flux than is Nb (at 14 nΩ μT^{-1}, but see [25]) very efficient shielding against stray magnetic fields will still be needed—MgB_2's buffer layer of choice, Fe, may provide this shielding [40].

5.3. *Peak surface field (RF critical field) and E_{acc}^{MAX}*

Typical ratios of peak electric (E_{pk}) and peak magnetic fields (H_{pk}) to the accelerating field (E_{acc}) for electron machines such as TESLA are:

$$E_{pk}/E_{acc} = 2.0 \tag{10}$$

$$H_{pk}/E_{acc} = 42 \text{ Oe MV}^{-1}\text{ m}^{-1}. \tag{11}$$

The maximum allowable values of all these quantities is limited by H_{pk}^{MAX}, namely the surface (or RF) critical field. Also known as the superheating critical field, H_{sh} is the field at which fluxoids begin to nucleate within the superconducting surface [27]. As mentioned above, at microwave frequencies H_{sh} lies above H_c in type-I superconductors and above H_{c1} (hence below H_c) in type-II superconductors—see equations (8*a*)–(8*c*) above. The distinction is moot for Nb ($\kappa = 0.78$) whose lower- and thermodynamic critical fields (0.17 and 0.2 T, respectively) are close together. For Nb, theory and experiment are in good agreement [30, 31]. But in high-κ superconductors such as Nb_3Sn the distinction makes a great difference. Estimates of H_{sh} based on 0.75 H_c (0.4 T [19]) and the results of experiment (about 0.11 T, i.e. 0.21 H_c [30]) were significantly different. No explanation was forthcoming; naturally both the validity of theory and the condition of the coating (granularity, roughness) were suspected.

For MgB_2 at 4 K ($H_c = 4290$ Oe [19]) with a κ near that of Nb_3Sn (roughly 20 cf [34]), and based on the Nb_3Sn observations, we might expect $H_{sh} = 0.22H_c = 940$ Oe in early samples, increasing to $0.75H_c = 3220$ Oe as the coating techniques become perfected. Then, based on the above H_{pk}/E_{acc} ratio of 42, we estimate E_{acc}^{MAX} to be 77 MV m^{-1}.

6. MgB_2 cavity coating—two-stage physical–chemical vapour deposition

A possible two-stage PCVD technique is based on the reacting together of Mg vapour with a pre-existing B coating. The first example of this is the well-known experiment by Finnemore *et al* [41] who exposed a W-reinforced B fibre to Mg vapour. The B fibres themselves are typically made by drawing a W filament (the 'substrate'), heated to 1200 °C, through a gaseous mixture of H_2 and BCl_3. Likewise researchers at Los Alamos National Laboratory exposed a B powder compaction to Mg vapour [42]. This same approach could be applied to the formation of a MgB_2 film on the surface of an RF cavity previously coated with B using established CVD technology [43, 45]. In the field of tokomak-fusion, plasma-vessel walls of stainless steel or Mo are coated with B in order to getter oxygen or other impurities. The B is deposited on the vessel wall by decomposition of various B-containing gaseous mixtures under the action of conventional glow discharge. Gaseous mixtures used in this CVD approach are: (i) D_2 + He + vaporized decaborane ($B_{10}H_{14}$) [43], (ii) He + borane (H_2B_6) [30], or (iii) D_2 + He + trimethylboron (TMB) [45]. One or other of these techniques could be employed to deposit the initial B coating, after which the heated cavity could be exposed to Mg vapour in order to form the final MgB_2 layer.

7. Summarizing conclusion

With an allowed maximum acceleration field, E_{acc}^{MAX}, of 20–100 MV m^{-1} and a BCS surface resistance, R_s^{BCS} (4 K, 500 MHz), of 2.5 nΩ MgB_2 represents an interesting possibility as a coating for superconducting accelerator resonant cavities. The higher H_{c2} of MgB_2 than Nb results in a slightly lower estimated trapped flux sensitivity, which is moot at present, R_{res} being dominated by the other residual term (an R_{imp} of about 1.3 mΩ). Improvements in coating techniques will help to reduce this value. With regard to coating techniques, and indeed base cavity fabrication, particular attention should be given to field emission and thermal breakdown and the manner in which these problems are being addressed during the fabrication of contemporary solid-Nb cavities—see sections 4.2 and 4.3.

Our calculations are based on 4 K operation. However, with a T_c of 39 K, MgB_2-coated cavities should be less susceptible to thermal breakdown than low-T_c ones. Superconducting materials for use at GHz frequencies at voltage gradients >40 MeV m^{-1} will require both low R_s (high T_c) and high H_{sh} values. At 39 K the T_c of MgB_2 clearly has the potential to reduce R_s^{BCS} if the films are well prepared and free from defects. Additionally, while the H_{c1} for MgB_2 is relatively low, the superheating critical field, H_{sh}, is higher than that of Nb. Presently, there is some debate about the exact roles of H_{c1} and H_{sh} in the determination of E_{acc} limits. However, the higher values of H_{sh} for MgB_2 do suggest the possibility of enhanced E_{acc} values. The exact roles of H_{c1} and H_{sh} should be further investigated. Techniques exist that may enable cavity-like structures to be internally coated with an MgB_2 film. The practicalities of these methods have yet to be addressed.

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